Analysis of Political and Trade Decisions in International Gas Markets: A Model-Based Systems Engineering Framework

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Abstract— **By taking a model-based systems engineering (MBSE) approach, a framework can be developed for long-term exploration of a complex adaptive system in multiple contexts. The framework uses MBSE tools to define the complex system architecture and modern internet state transfer and structured data format standards to integrate natural language descriptions, datasets, and models. These can constitute a knowledge architecture that can be used as a long-term research tool. The long-term goal is a framework that captures conceptual models of the complex system, data sets and relationships, dynamic models and simulations, and decision analytics within a common environment. This paper presents a scenario in which we evaluate links between transformations of complex natural gas systems and analyze political intervention into the Russian-European natural gas markets. In this example, we specifically examine geographical, physical (cross-border infrastructure), and commercial value streams through the prism of network analyses. This is one context of a more general model of international gas relationships and flows at multiple levels. The resulting framework provides insight into dynamic behaviors at multiple levels of the system, such as the emergence of infrastructure network and intricate relationships of strong corporate ties and knowledge networks, along with possible strategies for political and economic intervention. The primary goal of an MBSE approach is to capture interrelationships in the complex system at varying levels of abstraction, which enables a common reference for diverse models and datasets.**

Keywords— Multi-level modeling; Sociotechnical systems; Complex adaptive systems; Systemigram; Soft systems; Model-based Systems Engineering; Emergence; Emergent patterns; Social Network Analysis; Visualizations; Energy; Natural gas; Emergent patterns; Resilience

I. Introduction

Systems engineering continues to make great strides in developing tools that support larger and more complex engineering designs. However, complex engineered systems continue to evolve with only partial understanding of their effects on the larger enterprises they operate with or limited knowledge of the long-term behaviors that will emerge from the engineered "solutions." Our interconnected world is changing the way people, businesses, and governments operate, and powering many large global enterprises that interact in both intentional and unintentional ways. Modern natural language processing (NLP), data search, machine learning, and data visualization tools enable research that allows use to "see" previously hidden or emergent relationships. Associated computational models can project trends, explore effects, and guide future actions. However, we would like to capture the result of these activities in a more holistic model that captures resultant "theories" at different levels of the complex system. Over time, this can be used to build and refine a knowledge base that relates different behavioral aspects of a complex adaptive system across sociotechnical, socioeconomic, and sociopolitical domains. This project is assessing new methods and tools for exploring complex multi-domain, multi-layer, and multi-context phenomena by capturing various literature, datasets, data visualization results, and executable models into a common systems model that is designed to reflect the knowledge relationships in the area of interest. The authors could find no other examples of similar work in the area of geopolitical relations and oil and gas enterprises. However, we believe the approach to use multiple information-centric forms of assessment will become commonplace in the future. The challenge for the model design is accurately capturing the relationships between data parameters at each level of the enterprise.

Designing models that accurately reflect levels of abstraction and aggregation of information is a fundamental concern when modeling complex systems. Presently, there is a distinct lack of appropriate tools to assess thoroughly these aspects of complex engineered systems at the broader scale. Many existing models also fail to capture interactions between the variables. Generalized models, although they may reflect regional data, tend to model the behaviors of the system (i.e., natural gas enterprise) independently from regions of interest and then correct with factors that increase or decrease regional performance based on broad indices. Behavioral aspects of complex sociotechnical systems can be influenced at any level. The abstraction level of interest to the users of the model does not always match that of the model designers. In particular, when analyzing visual representations of data, the contextual frame of reference must be explicitly defined (individuals/groups, enterprises, sectors/domains, or environments) for both the collected data and the modeled interactions. The data analysis tools should effectively explore both the results of the analysis and the abstraction decisions in the analytical models. Modern data analytics can help with this. Similarly, with the

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explosive digitization of data, we have an unprecedented access to potentially valuable information that can inform and guide ecosystem decision-making. However, the sheer volume and complexity of the data can often become overwhelming, inevitably prompting a loss of the value of the data and possibility for competitive advantages it can create. The decision-maker's ability to systemically make sense, understand, and analyze ecosystem network structure and dynamics, diminishes rapidly [1]. Management of such networks requires significant coordination, collaboration, delegation, and monitoring, and existing approaches are deemed largely inadequate [2]. System engineering rigor can help with this.

Our work bridges traditional system engineering tools and wider views. We explore conceptual or visual models of the complex system, which are accompanied by narratives or scenarios that address the wider system views. Understanding the context and nature of complex systems begins with data collection, usually informed by observed phenomena that lead us to question our current understanding of the system behaviors. This process of collecting, analyzing, and communicating data is often referred to as "sensemaking" [3, 4]. Various representations in system science literature recommend using visual models to create insight and agreement on system boundaries with respect to the wider system, system interactions across the wider system, and system perspectives (often called mental models). Visual network analytics, which fuse interactive information visualization with complex network analysis, can be used to explore real-world data relationships and from that abstract models of system level interactions. The analysis is aided by taxonomies describing the initial model framework. As engineered systems generally fall into the class of sociotechnical systems, one can view the wider system as differing levels of an enterprise framework. Viewing the complex system as a multi-level enterprise provides a familiar structuring that helps visualize the wider system intent, clarify data abstractions between levels, and structure a meta-model which can be used to develop analytical models. We used a taxonomy and process developed by Rouse to guide the development [5, 6].

Using the international gas market as our focal point, this paper presents ongoing research in which we examine geographical, physical (cross-border infrastructure), and commercial value streams through the prism of network analyses. This enables our team to deduce new hypotheses concerning structural incentives and vulnerabilities that face state and non-state actors derived from their "centrality" within dense physical networks. We further distinguish the strength of commercial ties in the gas domain embodied by different types of strategic alliances, joint ventures, and peer-to-peer exchanges at the state and corporate levels within specific regions.

II. POLICY AND TRADE ANALYSIS

In a highly interconnected world, cross-sector innovations tend to diffuse across the large global enterprises much faster than policy or laws can react. There is a need to regularly revisit assumptions about "how the system works" to keep pace with the changes [7]. There are several areas in which policy and existing models are not sufficient to estimate change in complex environments. Areas of concern include regional variations to system effects and multi-level or multi-scale behaviors. Generalized models, while they may reflect regional data, tend to model the behaviors of the system independently from regions of interest and then correct with factors that increase or decrease regional performance based on broad indices. Many existing models also fail to capture interactions between the variables. In many cases, the models are generally accurate within one aspect of the system, but the assumptions put into the models reflecting other aspects are incorrect or no longer valid. Often, years can pass before policy makers begin to accept the fact that different dynamics are driving the system and the existing models are inadequate to predict trends.

Study of the sociotechnical behaviors of the system can provide insight to policy makers on emerging trends that can be used to adjust their assumptions of system operations and behavior. Corresponding gap analyses further aid understanding of what existing models can and cannot do. New assumptions can be played into existing models or new enhanced models to form an analytical basis for policy decisions. Such analyses early in the emergent cycles of system change inform more agile policy decisions. In the long-term, new models that capture more complex system behaviors can be developed and run on continually higher performance computing systems. This capability can inform policy makers of emergent areas outside their current knowledge-realm by enabling the exploration of system interactions.

Specifically, the different variables that influence behavior within these networks can be identified depending on the strength of ties and relative position of the physical infrastructure. Exogenous variables are identified to understand what is impacting or what can be impacted that will drive the overall behavior of the system, whether it is a natural disaster or state/terrorist attack. These processes and inter-relationships are modeled at the macro level to determine relationships in the network. The ties connecting these actors or nodes within critical infrastructure networks, such as natural gas pipelines, represent patterns of relationship, constituting a type of structure that constrains or facilitates the behavior of actors. Understanding these structural relationships is the central objective of network analysis. First, while current approaches tend to focus on either the flow of energy or the attributes of actors within energy networks, the analyses of structural and social relationships provide alternative ways to understand the influence and behavior of actors within a network. Second, structure can be used to identify the pathways through which information and knowledge, as well as materials flow. Third, structural relations are dynamic. Networks are not static, because physical and social relationships are constantly changing and evolving.

The global energy ecosystem is characterized by large and complex networks [7, 8]. Recent empirical studies underscore the rising density and complexity of gas infrastructure worldwide. Most notably, the cross-border gas trade is transforming from point-to-point pipeline delivery to webs of interconnections among various physical components (e.g. large diameter, interconnector, and reverse flow pipelines, storage depots, and LNG facilities) that are reinforced by diverse transnational business relationships among state and private energy entities. Further technological advances in both natural gas recovery and distribution will contribute to changing supply and demand behaviors. The impact of technology on upstream processing of shale gas resources is causing many energy forecasts to diverge. Technology enhancements will continue to add uncertainty to traditional supply and demand forecasting.

This changing structure of physical *and* social ties, which varies across regional gas system, presents unprecedented and multidimensional forms of interdependence among suppliers, transit states, and customers. While these networks become increasingly valuable with size, they introduce new forms of inefficiency, asymmetrical dependency, cascading effects, and political influence [7, 8, 9]. Today's networks are global and regional in character, consisting of public and private organizations, from different geographic areas and various market segments. They are coordinating, collaborating, partnering, and competing, to ultimately create and deliver energy products and services to end customers [10]. Therefore, an appropriate level of actionable insight into an energy ecosystem is very difficult to achieve [11] without systematic appreciation for the character of respective commercial ties among public and private actors within respective sectors. Lacking basic understanding of the intersection of significant economic, political, and societal relationships can lead decision and policy-makers to underestimate serious competitive threats and disruptive activities resulting in conflict and economic loss, as well as indirect and knock on effects of interdependent state policies (e.g. sanctions) and commercial activity.

In light of this shift toward more dense interaction within regional gas systems, we applied alternative network theories/analyses to discern emerging elements of geopolitical vulnerability, power, and influence. Network analyses focus on the *relationships* among actors or nodes. These specific relationships can be abstracted to phenomena that are more general in the system. Presently, foreign energy-related policy is focused on affecting access and value to sources, reserves, and commercial relationships. However, phenomena such as transit states or storage facilities owners have distinct nodal relationships that are not thoroughly captured by existing models. There also are foreign commercial entities that own or control a national infrastructure and pipelines that get lost in traditional analyses. In the long-term, the research will capture these integral cross-border relationships at macro-, meso-, and micro-levels to offer both rigorous and rich understanding of network values and relative influence within regional systems. Embracing a socio-technical approach to network analysis, the project offers a framework for assessing market and political drivers across gas sectors using MBSE tools for long-term research. This provides insight on emergent properties in the system that would not normally be captured in existing operational and economic models.

III. Multi-Level Methodology

This project follows a methodology that uses a 10-step data collection and characterization methodology for modeling complex systems [5]. Steps 1-4 were carried out in the first phases of the project and outlined in a previous paper [13]. This work reflects steps 5-8 of the process, with steps 9-10 remaining as future research. The steps are summarized in Table 1.

This paper extends the systems modeling results from the regional scenarios into data collection and visualization to refine the interrelationships and explore scenarios that are more detailed. The visualizations from Step 3 provide the basis for in-depth discussions and lines of reasoning, and a tool to select the correct engineering model representations for further work. Steps 5-8 address model representations and model design. These steps are done by a multidisciplinary team of international policy scientists and system engineers.

The initial phase of this project developed a descriptive model using systemigrams [12] and the example scenario of the European and Russian natural gas landscape

Table 1. 10 Step Multi-Level Methodology Application

	Title	***Application***
Step 1	Decide on Central Questions of Interest	These investigate how the enterprise will change over time.
Step 2	Define key phenomena underlying these questions	Key phenomena identified in workshops and with subject-matter experts underlie variables associated with the questions of interest.
Step 3	Develop one or more visualizations	Qualitative descriptions detail the system's current and future state that is visually modeled in a systemigram to capture system interactions.
Step 4	Determine key tradeoffs that appear to warrant deeper exploration	Step 3 visualizations provide the basis for in-depth discussions and a tool to select correct engineering representations for further work.
Step 5	Identify Alternative Representations of These Phenomena	Visualizations and social network models will be included in the computational model to explore phenomena in more depth.
Step 6	Assess the Ability to Connect Alternative Representations	This determines how models, diagrams, and computational properties relate for effective data synthesis and extraction.
Step 7	Determine a consistent set of Assumptions	A set of assumptions that will hold true across the representations must be determined in order for the computations to be meaningful.
Step 8	Identify Data Sets to Support Parameterization	Identify data sources and data needs for collection for specified parameters.
Step 9	Program and Verify Computational Instantiations	Develop a design model for production runs and instantiating interactive visualizations with graphs, charts, sliders, etc.
Step 10	Validate Model Predictions Against Baseline Data	Validate the resulting computational model. The model is a means to explore "what if" scenarios to gain insights for further empirical study.

development to examine socio-behavioral aspects of the system. This provided understanding of enterprise organization and response to emerging systemic changes. As a whole, the initial work indicated the need for increased development of physical, economic, and social/value network models to augment existing resource and capital modeling. In addition, it indicated that network vulnerability models are a future area of interest. In this analysis, the conceptual modeling tools are used to guide the network visualizations of information created in the project methodology steps. Network models and network visualization tools are used to represent large numbers of entities and relationships. The resulting visual analytics allow experts to abstract more general phenomena about system behaviors from the network metrics that are selected in the model.

IV. CONCEPTUAL MODELING

Conceptual models formally capture the required insights needed for identifying questions of interest as use cases for the network modeling tools. Four types of conceptual modeling should be explored to capture comprehensively the "sense" of a complex system: concept mapping, structural analysis, network analysis, and behavioral analysis. When studying future situations of complex enterprises, mapping the concepts in the sociotechnical system provides an initial framework for elaboration of sector-specific questions by capturing variables that affect system behavior. Concept maps are learning tools that represent complex system architecture at multiple levels of abstraction via descriptive text and formal diagrams. Structural and behavioral models are well known in systems engineering, but networks and particularly visual network analysis, are used much less often.

In the conceptual design of a decision analysis framework for use of the information derived from the network models, it is useful to explore the system in past, current, and future states. The conceptual models are used to bridge existing (historic) data with the future system characteristics developed in foresight activities. This is often done using mathematical equations that extend broad trends that are created from aggregated data. However, the natural gas enterprise is in a period of innovation driven change, and historical data is not sufficient to describe the effects that lower level enterprise decisions within the gas system have on inter-state coercion or aggregated effects using trend data. Traditional assumptions of operational or economic drivers in these enterprises no longer accurately predict future geopolitical risk or vulnerability. We used expert-defined scenarios to identify possible future system entities and relationships and aggregated phenomena that were then captured in the conceptual model. The conceptual models are maintained as a research tool to explore deeper issues with observed phenomena that exist outside of normal physical or socioeconomic models.

A. Capturing Concepts: The Systemigram

Boardman's systemigram [12] is useful for representing sociotechnical concepts as it combines structured narrative (native to policy analysts) with diagrams generated from the text. The diagrams create an initial structuring of a system model. The questions and variables identified in steps 1 and 2 were taken into consideration when researching the scenarios and preparing the narratives and diagrams for systemigram creation. Scenario development addresses and selects representative cases in order to assess leading indicators and issues that arise from the scenario description, key drivers, and inhibitors within each scenario, and expected outcomes associated with each scenario. This is done at each level of the sociotechnical enterprise model to address multi-level behavior. The use of the systemigram tool together with network models of large data sets represents a novel approach for exploration of emergent phenomena in a complex sociotechnical system. Qualitative descriptions developed via narratives detail the system's current and future state, which is then visually modeled in a systemigram to capture system interactions. Results from the visual model not only depict system structure, but also depict how it works and will work in the future.

B. Application Development: European and Russian Natural Gas Landscape

Our previous paper [13] included one of four regional scenarios selected for domain level evaluation, the Development of the European and Russian Natural Gas Landscape, consisting of a narrative and systemigram. Key phenomena are captured and described in terms of inputs, processes, and outputs in the domain. The example systemigram visualization shown in Fig. 1 was captured from an initial exploration of the emerging European gas network [7]. This portion of the diagram shows the relationship between transit states and supply/demand in the context of the EU and Russia. Although the supply chain aspects of transfer and storage in transit states are well known, the geopolitical relations between transit states and neighboring supply and distribution hubs are seldom studied. The phenomena represented in the diagram comes from a discussion of the coercive leverage Russia is attempting to apply in Eastern European transit states to work around EU third party restrictions on gas monopolies. We are not aware of any other efforts to model these relationships. Different geopolitical regions or separate levels of the sociotechnical system can be modeled by using multiple systemigrams to provide insight into similarities and differences across systems. The systemigram captured a unique set of interactions, emergent phenomena, and scenarios that provided identification of areas of future exploration. This included differing strategies of resource endowment, capital access for development, bilateral agreements and knowledge networks, emergence in transit infrastructure, and the ability of technology to change how flows are managed and priced. The systemigram showed many complex interrelationships between governments, energy companies, and in the nations in which they operate. In this study, these areas can be further explored via epoch-era analysis; modeling resource and knowledge flows; and comparative analysis of regional and global differences. Epoch-era analysis is an approach to capture changes in context (both time and space) that

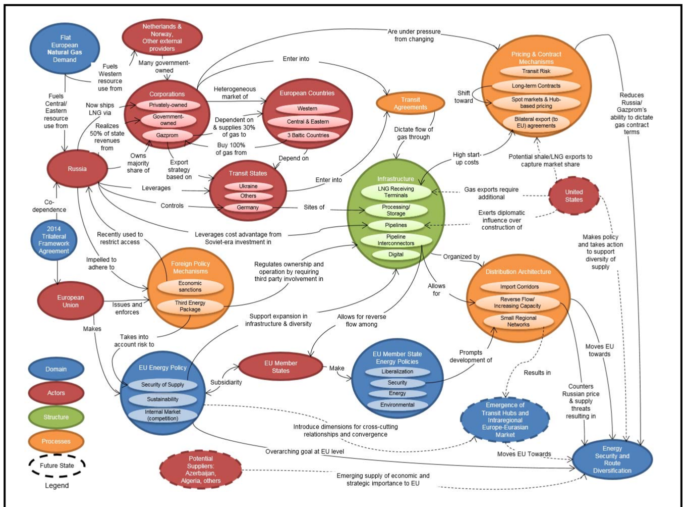

Fig. 1. Systemigram Visualization: European and Russian Natural Gas Landscape

represent shifts in overall system behavior [14]. Viewing aspects of the systemigram as change drivers allowed us to create a timeline that breaks down the system-level aspects and actors according to the specific events and activities. The timeline of EU-Russian related energy events and conflicts (Fig. 2) was classified per relationships in the systemigram into three categories: market & economy factors, EU policy & governance, and security & conflict. This analysis led us to classify our data sets into epochs associated with a common political context of the 2006 and 2009 EU/Russia "gas wars" and three associated time-periods: prior to 2006, 2006-2009, and 2009-present. While these epochs focus on security & conflict, we could also analyze epochs related to EU policy & governance and market & economy changes. The systemigram allowed identification of the deeper-rooted systemic behaviors and flows, presented in the form of knowledge flows and resource flows. These can also speak to regional and global differences of the natural gas enterprise, which is undergoing vast transformations that are driving behavior and interaction changes rippling through the levels of the system globally. These three areas are further refined and explored in the network analysis.

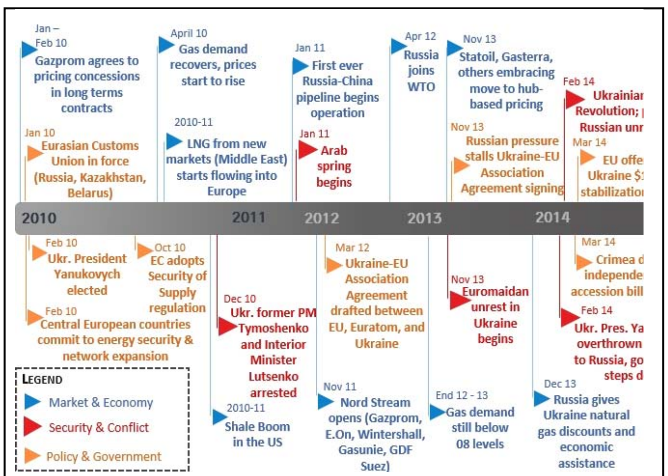

Fig. 2. Excerpt from Timeline on European and Russian Energy & Natural Gas Related Events

V. Visualizations and Social Network Application

Network analysis is a powerful tool for understanding the structure of physical networks, the position of actors within those networks, and how that position affects the ability of state and non-state actors to exert leverage, influence, and power within the global gas infrastructure. Network analysis views power as a function of both an actor's capabilities and structural position within a network, not solely as a function of material capabilities. By drawing upon insights from network analysis to discern different measures of centrality within the cross-border physical infrastructure or "strength" of organizational ties, we are able to identify incentives for international conflict and cooperation. The data also illuminates specific points of vulnerability or value within respective regional networks to attack or manipulate for strategic effects. By mapping data to visual encodings, visualizations of energy networks make the "what, why, how, and who" explicit. Given that the structural aspect of inter-organizational energy networks is of particular interest, we focused on developing graph visualizations. When modeling the gas sector, the key boundary conditions are geographic (regionally defined suppliers, customers, transit states), physical (infrastructure directly tied to cross-border delivery of gas), economic (contracts, public/private institutional ownership), and organizational (development, ownership, control, and operation of related physical infrastructure). Physical and economic network analysis was used to identify strength and control of resource flows. Social network analysis was used to identify important non-physical characteristics of a network, including, but not limited to, points of strength and weakness, redundancy, location of brokers, alliance dynamics of the firms and states within the network, past relationship dynamics, shared resources, or network density. Changing network relationships over time related the analyses to the three geopolitical epochs and associated economic, policy, and political conflict behaviors.

A. *Centrality and influence in emerging physical gas networks*

Identifying the most prominent actor in a physically or socially interdependent relationship is a principle concern from a network perspective. An actor's location within a network depicts prominence, which functions as its measure of centrality. Centrality is a measure of an actor's ties or relationships within a network, and the most central actors in a network are referred to as hubs. A prominent node is more central and thus has greater visibility to others within the network, while a prestigious actor is the recipient of many ties within a network. In order to identify critical nodes and locations of strength or weakness within gas infrastructure networks, we used three measures of centrality: degree centrality, betweenness centrality, and eigenvector centrality. A node's position within a network's structure is critical for identifying the type and quality of its influence over supplier, consumer, and physical

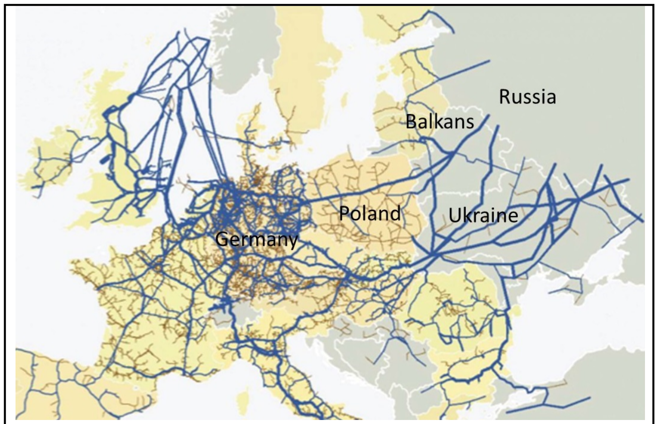

Fig. 3. Physical infrastructure of the European natural gas network [16].

infrastructure. The concept of centrality also can help to discern network resilience or to pinpoint network weakness or a certain actor's prominence of stronghold. Actors or nodes with a high betweenness score can act as gatekeepers, controlling the flow of information, gas transport, money, or even the ability to coerce other actors. Identifying factors that alter betweenness centrality (such as storage or reverse flow) is critical for evaluating infrastructure network resiliency. Eigenvector centrality can be useful for identifying prominent firms, regional networks, or critical facilities.

B. Methodology and Tool Application

In this component of the project, we followed several processes for visualizing inter-organizational energy ecosystem networks: identification of design requirements; data identification, extraction, and curation; boundary specification; network construction; metric computation; and visualization. Our methodology does not self-propel from one stage to the next, but involves an iterative "human-in-the-loop" approach. At each step, we tested and evaluated the system with actual decision and policy makers [15].

Given these caveats, the plausibility of alternative measures of centrality in gas networks were probed using three network analyses followed by comparative analysis of the network visualizations and scores. A physical network analysis of existing natural gas pipelines across Russia and the EU highlighted regional differences in network density and centrality. This was accompanied by a dataset representing long-term contracts associated with the same regional contexts. The combination of these represents regional power and influence as determined by resource flows. Fig. 3 depicts the density of physical networks, which has seen a major shift in importance of flows to the Russia/Germany Nord Stream pipeline. Physical network scores reflect network strength and integration between Russia and Germany that is three times more central than any other supply line in the EU. A separate social network analysis provided insight related to qualitative case studies of contemporary, high profile bouts of cross-border coercive gas diplomacy across different regions. Our visualizations and initial findings signaled strong corporate strategic relations, as captured in fig. 4, which shows a full timeframe of Gazprom's centrality in the global knowledge transfer domain. The dataset was analyzed in the three epochs and grouped according to sub-region and country. This enabled clarity of captured major actors, discernment of power positions, and enhanced visualization readability. Network construction is based on firms (nodes) and interfirm relationships (edges). The betweenness centrality centered on formal enterprise relationships of Gazprom and its subsidiaries. Node size reflects betweenness centrality of the firms, color coded by country. The link quality is based on knowledge transfer model (type of relationship), which signals both centrality and strength of formal affiliations. The qualities of interfirm relationships were weighted by the knowledge value exchanged and reflected in the linewidth of the links. Knowledge exchange is weighted according to Joint Venture (highest), R&D and Marketing, Technology Transfer, Supply Chain, Manufacturing and OEN, Exclusive Licensing, and others (lowest).

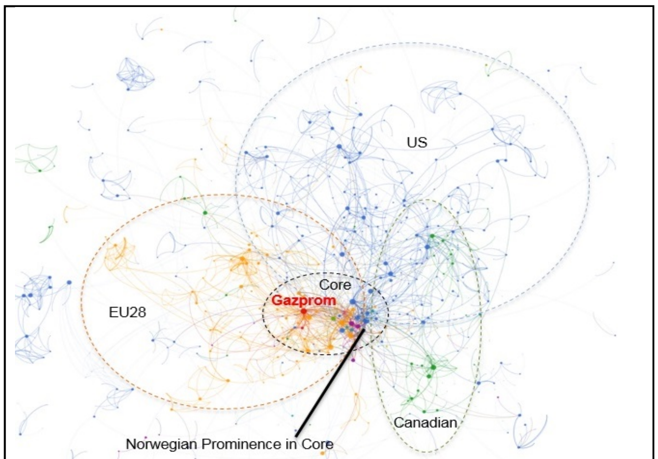

Fig. 4. Visualization of Regional Natural Gas Knowledge Networks.

We also used aesthetic criteria to improve the readability and effectiveness of our graphs, including minimization of edge crossings, total drawing area, and maximizing symmetries to reduce visual clutter. Figures 5-7 show examples of changing knowledge relationships between Russia-Gazprom and corporations in EU countries across the three epochs in the northern European region. Mature relationships in 2006 exist between Gazprom and firms in Norway (yellow) and Finland (Green). Knowledge relationships grew between Gazprom and Germany (blue) in the 2006-2009 epoch and have been increasing with Poland (purple) in the 2009-present epoch.

Similar analyses provided further regional insights, such as the Balkan region, which has extensive contract relationship solely with Gazprom, yet lacks physical or knowledge network power. Gazprom has significant network centrality and contracts through Ukraine, but no knowledge relationships. Additional context was discerned from previous conceptual models and baseline research that allowed comparative analysis of the models. This includes comparative analysis of the mixed intensity and outcomes of Russia's successive gas pipeline politics and conflicts with Ukraine in 2006, 2009, and 2013-15, which is mapped against market/economic factors and related EU-level and

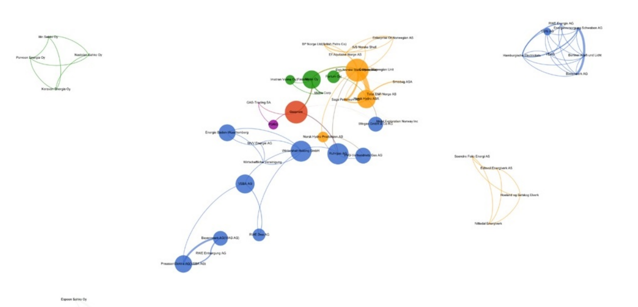

Fig. 5. Visualization of Natural Gas Enterprise Network Relationships to 2006 "Gas Wars".

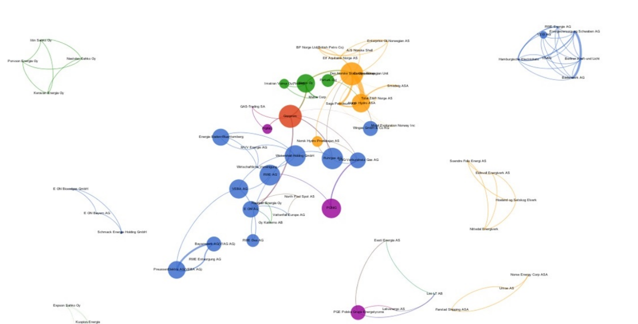

Fig. 6. Visualization of Natural Gas Enterprise Network Relationships during 2006 – 2009 "Gas Wars".

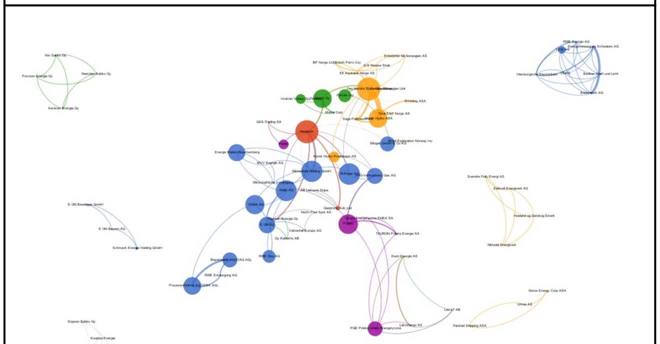

Fig. 7. Visualization of Natural Gas Enterprise Networks From 2006 to Present.

NATO policy measures. Similarly, through the application of conceptual models and systemigrams, we can apply alternative network measures of centrality to assess the relative influence of regional infrastructure hubs for explaining variable bouts of escalation of contemporary resource competition in the East and South China Seas and/or Arctic. Comparative analysis of the strength of current oil & gas sanctions on Russia from the US and EU reflect the potential for reverse sanction impacts on German firms based on the high physical and knowledge relationships, likely resulting in the current application of weaker sanctions from the EU compared to US policy.

VI. Combining Qualitative and Quantitative analyses For Analysis of Gas Networks

For our study, systemigrams are useful conceptual models that support the network analyses visualizations and act as learning tools for knowledge building in decision-analysis. They were used to identify areas of exploration to be augmented or further tested in the network visualizations. The systemigram provides the architecture of the system to guide development or use of computational models. They capture the general system structure at the domain ecosystem level (highlighting policy and political relationships) and at the energy sector level (highlighting institutional relationships) [7]. This enables exploration of key questions, such as how US and EU sanctions flow through these relationships, by closely capturing how there might be different impacts at separate system levels. The narrative form of the systemigram specifically supports identification of different emergent epochs and eras. The conceptual models and systemigrams also support specification processes for additional network-modeling requirements: namely boundary specification and ontology development for data extraction. In a complex sociotechnical system, determining boundaries between the system of interest and the wider external context can be difficult and lead to incorrect assumptions about what variables are internal, external, or across, the system boundary. A descriptive conceptual model such as the systemigram can describe interrelationships in both local and global contexts that support agreement on the boundaries of interest.

The analyses from the conceptual models identified prospective key variables of interest and changing dynamics of the systems, which will drive data aggregation, system dynamics development, foresight analysis, and engagement with subject matter experts in the latter stages of this project. They also will be compared and contrasted to the findings generated in the earlier steps of our methodology to discern the relative significance of dynamic changes to the gas landscape for international security. Looking at energy networks in relation to infrastructure and social capital provides insight beyond the impact of changing consumption behaviors and energy flows through pipelines. With a comparison across different regions, and identifying key nodes within these regions, we capture direct and indirect relationships that have not been reflected in current studies of strategic dyads.

Through application of different measures of centrality, betweenness, and social ties, we develop greater understanding of the dimensions of power and influence to explain coercion, but also provide insight into regional conflict. By applying a range of variables to our network models and visualizations, this will illuminate potential sources/location of conflict, attacks on infrastructure, and non-military forms of statecraft. For socio-economic reasoning, this goes beyond looking only at sanctions and influential roles of key agents and actors, but can include strategic use of energy infrastructure, cut-offs, and use of subsidies or loan guarantees as inducements both to exploit vulnerabilities and bolster resilience and cross-border governance. The exploration of conceptual relationships and network relationships as initial steps allow us to understand more thoroughly the structural components, interfaces, and behaviors of interest before trying to design computational models. There are strong regional differences across the EU with respect to dependence on Russian energy and security of supply that cannot be aggregated to a general model of the EU. Dynamic models of the feedback between policy changes and geopolitical behaviors need to reflect both regional differences and types of flow. Further exploration of specific behaviors across the regions will allow construction of computational models that balance regional and national policy.

VII. Conclusions and Future Work

This study builds off the initial phases of our project, wherein we developed a framework for modeling the complex sociotechnical enterprise representing emerging global natural gas landscapes. The data gathered during network and conceptual mapping provides rich insight into policy issues and ultimately aid in identifying to decision-makers worthwhile areas of future near and long-term exploration. Working with experts in energy and security domains enabled the development of socio-technical models to capture modeling constructs across global energy enterprise layers. For this research phase, we focused on developing conceptual models and interactive data-driven visualizations of complex inter-organizational energy networks. The generation of interactive visualizations and models provided tools to update and scrutinize alternative scenarios in light of changing events and substantive feedback from both scholars and policy practitioners.

By drawing upon insights of social network analysis and network theory, we discern different measures of centrality and strength of ties. This enables identification of incentives for conflict and cooperation attuned to growing density and complexity of the contemporary gas landscape. This allows us to illuminate specific points of vulnerability and value within the network. Broadly, our results capture dynamic relationships in natural gas networks with relation to changing infrastructure. The results will expose concrete ties that bear directly on attacks on energy infrastructure, coercive energy diplomacy, and key reserves prone to serve as objects for conflict. This framework will continue to be applied to current modeling and simulation efforts and computational design. The framework and associated MBSE toolset can also be used as a conceptual asset for both experimentation and an artifact for engaging non-technical stakeholders. The approach considers the conceptual asset as the core of a "campaign of experiments" – incremental simulation and real-world measurement of designed change.

The overarching aim is to demonstrate the value and applicability of such novel MBSE computational tools for policy and decision-making contexts, evaluate their effectiveness, and investigate how actionable insights can be achieved. From a computational perspective, our future research will identify and validate the specific design requirements and decision support needs of prototypical users (e.g. energy policy makers, analysts, and executives), create multiple coordinated visual representations that match their needs, and develop an intuitive user interface with novel interaction techniques. As data and executable models are added to the framework, the accuracy of the data and value of the models will be validated with subject-matter experts in workshops. The workshops explore existing data and emerging changes that are reflected in emerging relationships of the system to arrive at an understanding of how the enterprise is organized and how it might change. New assumptions can be played into existing models or new enhanced models to form an analytical basis for policy decisions. This research will lead to the development of the first interactive visual analytic system that generates critical insights into the structural, compositional, and temporal nature of large-scale complex inter-organizational energy networks.

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